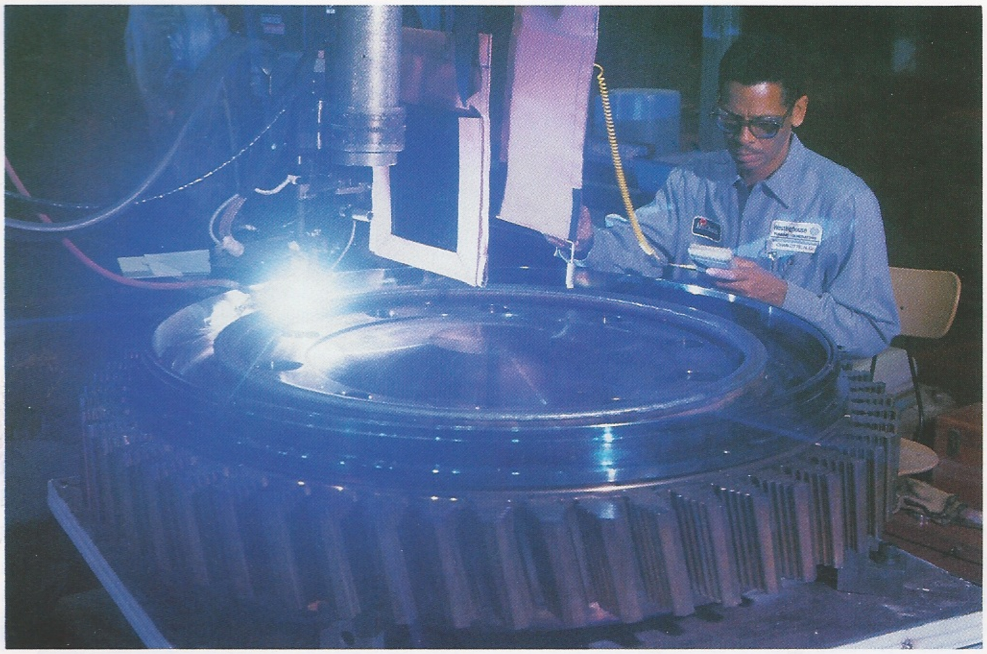
WELDING & REPAIR TECHNOLOGY FOR FOSSIL POWER PLANTS



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WELDING OF COMBUSTION TURBINE ROTORS AND DISCS

T.L. Driver
D.R. Amos
Westinghouse Turbine Generator Plant
P.O. Box 7002
Charlotte, NC 28241-7002

R.E. Clark (retired) - formerly of:
Westinghouse Electric Corporation
4400 Alafaya Trail
Orlando, FL 32826-2399

Abstract

Weld repair of steam turbine rotors and discs by Westinghouse has been performed successfully and has proven itself in operation for the last 15 years. Since 1978, over 200 low pressure (LP) rotors and discs have been weld repaired using the Gas Tungsten Arc Welding (GTAW) process. This process yields properties equal to or better than the original rotor/disc forging for LP alloys. In 1987, the GTAW process was extended to include repair on high pressure (HP) rotor alloys. Since that time, over 45 high pressure and intermediate pressure (IP) rotors have been successfully weld repaired and returned to service. The program has also been successfully extended to non-Westinghouse rotors of both the LP and HP/IP alloys.

Recently, to meet the demand for repair of combustion turbine alloys, a development program was initiated to make a step increase in the current LP welding process and filler materials from 100–110 ksi weld material yield strength (on LP alloys) to 140 ksi needed on many areas of a combustion turbine. The challenge to increase the strength by 30% could not be achieved at the expense of the other critical properties, particularly toughness.

This paper first reviews the successful LP and HP welding programs which were fundamental building blocks for welding combustion turbines. Secondly, the development and testing of a new filler material for welding combustion turbines is reviewed, which demonstrated the ability to achieve approximately 135 ksi yield strength. This new program was implemented on lower stress areas of two production parts which are described in part three. The paper concludes with a summary of possible future work to achieve nominal yield strengths near 145 ksi.

History of Rotor Welding Development

Process Development — Low Pressure (LP), High Pressure (HP) and Intermediate Pressure (IP) Turbine Rotors and Discs

Design Considerations

Repair welds on low pressure (LP) turbines are made on all parts of rotor and disc forgings. For each repair weld, special attention is given to the following areas:

- Stress corrosion cracking susceptibility
- High-cycle fatigue
- Weld joint geometry

The properties of the weldment are controlled by the filler material and the welding process. A specific heat of filler material is selected to optimize the repair weld for the mechanical properties desired. For some repairs, the filler metal selection actually improves the rotor properties for a particular environment or operating condition.

Repair welds on high-pressure (HP) rotors are made primarily to the control stage area. Welds to almost every other area of a HP or IP rotor have also been accomplished. The two most important criteria that are considered when a weld repair to a HP rotor is proposed are:

- Stress in the heat-affected zone (HAZ)
- Operating temperature

These criteria affect creep properties, which are the design limiting factor in weld repairs to HP rotors.

Although the properties for HP/IP welds are primarily dictated by the filler material, in creep-sensitive zones the welding procedure takes a more critical role. A precisely controlled multi-layer bead sequencing technique is implemented to control the more critical role. A precisely controlled multi-layer bead sequencing technique is implemented to control the properties of the HAZ. Qualification tests for the HP/IP rotor welding program were conducted on specimens through thickness across the weld, HAZ and base metal to fully test and develop this special technique.

A complete listing of all characteristics relevant to LP, HP and IP rotors that have been evaluated and tested are shown in Table 1.

Area	Type of Tests Performed	LP	HP/IP	CT
Weld	Tensile, Yield Strength, Ductility	X	X	X
	Impact/Toughness	X	X	X
	High Cycle Fatigue	X	X	X
	Low Cycle Fatigue	X	X	
	Fretting Fatigue	X	X	
	Wear	X	X	
	Stress Corrosion Cracking	X	X	
	Fracture Mechanics	X	X	
	Residual Stress Measurement	X	X	
	Hardness	X	X	X
	Microstructure	X	X	X
	Creep		X	X
	Stress Rupture		X	
	Hardness	X	X	X
	Microstructure	X	X	X
	Creep		X	X
	Stress Rupture		X	
	Chemistry	X	X	X
	Temper Embrittlement	X		X
	Thermal Expansion		X	X
HAZ	Impact/Toughness	X	X	X
	Stress Corrosion	X	X	
	Fracture Mechanics	X	X	
	Residual Stress Measurement	X	X	
	Hardness	X	X	X
	Microstructure	X	X	X
	Creep		X	X
	Stress Rupture		X	

Table 1

A wide variety of rotor materials have been qualified for repair welding using the automatic gas tungsten arc weld process (cold wire). The LP alloys are the complete range of commercial NiMoV and NiCrMoV alloys. The HP or HP/IP rotor specification is similar to ASTM A470 Class 8 and is used for all of the HP qualification testing. We have successfully made various repair welds on the following compositions:

Component	**Composition**	**ASTM Specification**
LP Rotor	2.5 NiMoV	A470, Class 2
LP Rotor	2.5 NiMoV	A470, Classes 3 & 4
LP Rotor	3.5 NiCrMoV	A470, Classes 5, 6, 7
LP Rotor	2.0 NiMoV	A293, Classes 2 & 3
LP Rotor	2.5 NiMoV	A293, Classes 4 & 5
LP Disc	2.8 NiMoV	A294, Classes 2, 3, 4, 5, 6 Grades B & C
LP Disc	3.5 NiCrMoV	A471, Classes 1, 2, 3
HP Rotor	CrMoV	A470, Class 8
Generator Rotor	2.8 NiMoV	A469, Classes 2, 3
Generator Rotor	3.2 NiMoV	A469, Classes 4, 5
Generator Rotor	3.5 NiCrMoV	A469, Classes 6, 7, 8

Table 2

Quality Requirements

For LP rotor repairs, every heat of weld wire from a new supplier is subjected to tensile and Charpy V-notch tests. Tensile tests are conducted over a wide range of postweld heat treatments, enabling properties to be optimized for a particular rotor or disc. Once a stable pattern of test results is established with this supplier, a model is developed which can then predict the yield strength at various postweld heat treatments for future heats of wire.

The historical database that Westinghouse has collected for HP/IP weld wire gives information needed to predict yield strength of individual heats of weld metal. Should the customer request further testing, several all-weld stress-rupture and tensile tests can be performed to show that the heat will meet strength requirements following the postweld heat treatment.

All weld repairs are inspected by magnetic particle (MT) and ultrasonic (UT) techniques. The weld repair must meet the inspection requirements required of the original forging. The MT and UT inspections are repeated following postweld heat treatment to assure the final quality of the weld.

Historical Overview of Rotor and Disc Weld Repairs

Weld repairs have been made to a variety of rotors and discs. For each category of repair, a full-size mock-up was performed before that segment of the program could be implemented. Table 3 summarizes the welds that have been made since 1983.

In the period from 1983 to 1993, the activity in rotor welding has increased by 660% when compared to the number of orders for 1983.

Component	Type of Weld	Quantity to Date
LP Rotor	360° steeple repair	126
LP Rotor	Single steeple repair	18
LP Rotor	Glands, seals, other misc. areas	10
LP Rotor	Weld new end on shaft	4
LP Rotor	Expansion of disc width by 2"	26
Jackshaft	Misc. repairs	7
Extension Shaft	Repairs to main shaft	17
Boiler Feed Pump Rotor	Steeple repairs	10
Single Case Rotors	360° steeple repair	3
LP Disc	360° steeple repair	11
LP Disc	Other repairs	9
LP Shafts	Disc seats	4
HP Rotor	Control stage blade attachment area	34
HP & IP Rotors	Other steeple repairs	5
HP & IP Rotors	Other areas	5

Table 3

Welding of Non-Westinghouse Turbine Rotors

A natural extension of our LP and HP/IP rotor welding processes is the repair of non-Westinghouse equipment. In just the past three years, several non-Westinghouse rotors of both the LP and HP/IP alloys have been successfully weld repaired, reverse engineered and returned to service.

When considering a repair of this variety, the following topics must be addressed:

- Design of the blade attachment or other area to be repaired
- Location of the HAZ
- Tempering temperature of the rotor
- Mechanical properties of the rotor

To answer these questions, a significant amount of testing is performed both prior to cutting off the damaged area and following the cutting operation. Because a wide selection of filler metals are stocked, it is possible to closely match the wire to the specific rotor properties after postweld heat treatment.

For LP repairs, the yield strength of the weld build-up can be optimized to help prevent reoccurrence of the damage the rotor incurred in service. Once the weld is completed, the area is remachined to the original configuration through an intensive reverse engineering effort. Since this program began in 1991, 10 rows have been restored on LP rotors encompassing various blade attachment configurations.

The rotor welding program is applicable to non-Westinghouse CrMoV alloys as well. The same four topics mentioned above are also a concern with CrMoV rotors in addition to operating temperature. Successful implementation of the rotor welding process to the blade attachment area of the last IP stage of an IP/LP rotor was first performed for a

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As a result of the success of our welding program in welding non-Westinghouse rotors, rotor welding facilities are being expanded in 1994.

Welding of Combustion Turbine Rotors and Discs

Design Requirements for Combustion Turbine Repair Welds

Repair welds on combustion turbine rotors have similar requirements to the LP repair welds except that the required yield strength is at the 140 ksi level versus the 100–110 ksi level of LP welds. At the start of the program to develop combustion turbine weld repair, the following design objectives were set forth:

- 140 ksi yield strength in the weld
- Impact strength equal to or better than the disc material
- Fracture Appearance Transition Temperature (FATT) equal to or lower than the disc material
- High-cycle fatigue strength equal to or better than the disc material.

These objectives are similar to those set forth in the LP program and were applicable not only to the weld metal but also to the HAZ. Initially, repairs would be limited to areas that were exposed to service temperatures under 700°F.

Quality Requirements

During the development phase of a new program, the quality requirements imposed on the test welds are more stringent than those placed on the original disc forging. In order for the process to be considered capable of producing production welds that meet the design requirements, the test plates must meet an inspection criteria four times more sensitive than is used in production of the disc forgings. This scanning level is also used in production to watch for minor process variations that could cause rejectable indications, resulting in costly repairs and schedule delays. Frequently, productions welds, through careful attention to detail, are found to be free of indications at the test plate quality inspection level.

Welding Development

Welding Process Selection

The first step in development of this welding program was to choose from one of two welding processes. Although both Submerged Arc Welding (SAW) and Gas Tungsten Arc Welding (GTAW) have been used by Westinghouse in welding of LP turbine rotors, the GTAW process had the highest probability of approaching the design and quality requirements stated above. The GTAW process produces a refined grain structure which has been shown in both the LP and HP programs to be crucial in obtaining the desired mechanical properties. The GTAW process by design is also a very clean process (no flux, slag, hydrogen problems). An ultra-clean process is very desirable at the higher strength levels that would be produced in this program.

Filler Material Development

The current filler metal compositions used for the LP and HP welding programs were determined unsuitable for repair of combustion turbine discs primarily due to their low strength level (95-110 ksi). Thus, a new filler metal had to be selected which would not only meet the strength levels of the turbine disc but also the cleanliness requirements. A nominal 140 ksi yield strength wire, which will be referenced herein as "W140," was selected. This wire was a richer alloy in certain key elements than our present LP wire. These key alloy elements are known for producing higher strength levels, so this wire appeared to be an excellent starting point and testing was begun.

Test Plate Parameters

Three test plates were welded using the amps, volts, wire feed speed, travel speed and gas flows that are presently used on our LP welding program. Only stringer beads were used with no oscillation of the torch. Each pass was wire brushed clean and ground, if necessary, prior to depositing subsequent passes. The main change in parameters was that different preheats and interpass temperatures were utilized to optimize the properties while safeguarding the deposited metal from cracking. Large plates were welded with 3" of weld build-up being deposited over a 9" length. This allowed for producing test specimens that crossed the weld, HAZ and base metal.

Testing Program And Results

A rigorous testing plan was developed to assure that the weld metal chosen was uniform in properties and could meet the demands of combustion turbine rotors in service. The main areas of testing involved tension, tension vs. preheat-interpass, Charpy impact, high-cycle fatigue, hardness and metallographic. Results and discussion of each of these tests are presented in the following paragraphs. For a complete listing of the tests performed, see Table 1.

Tension Tests

Because of the high strength of the combustion turbine discs, tension testing was of great interest in this program. Twenty-six specimens were tested at various postweld heat treatments and a few in the as-welded condition. The results for all-weld metal tension tests are shown graphically in the chart below:

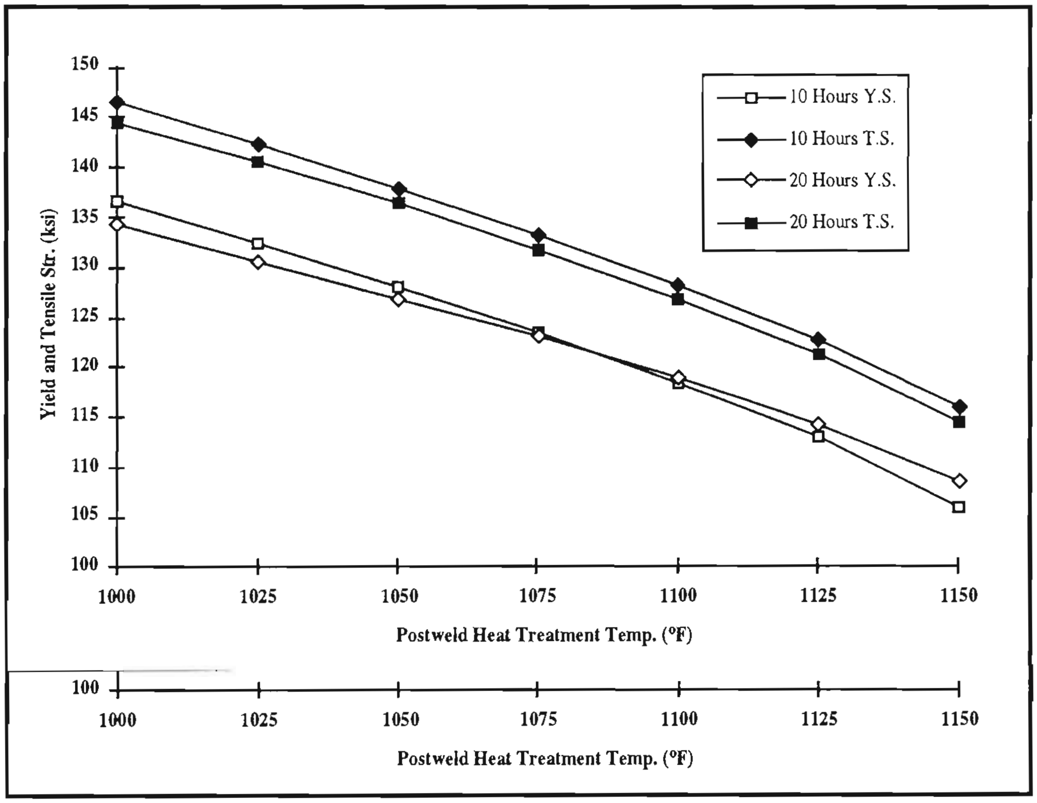

Chart 1

When the rotor tempering temperature is known, these tests provide information to choose a postweld heat treatment that will optimize the strength of the weld metal without jeopardizing the strength of the rotor. These results were typical of other testing that has been done on other types of filler material. As can be seen in Chart 1, even at the lowest postweld heat treatment temperatures, the goal of 140 ksi weld metal yield strength was not met with this filler metal composition.

Tension tests were also made transverse to the weld, with the heat-affected zone located at the specimen mid-gage length. All specimens failed in the lower strength weld. This data verifies that the heat-affected zone is not the weak link in the weldment. We have never observed heat-affected zone failures for any type transverse weld test in any NiCrMoV rotor weld testing program.

Because of the higher strength and alloy content of the high-strength disc materials, it was important to consider the effect of the preheat-interpass temperature on the weld tensile and yield strengths. For the second phase of tension testing, three test plates were welded, using three different interpass temperatures. Tensile and yield strengths are plotted versus the three preheat-interpass temperatures. They show a drop in yield strength with increasing preheat-interpass temperature.

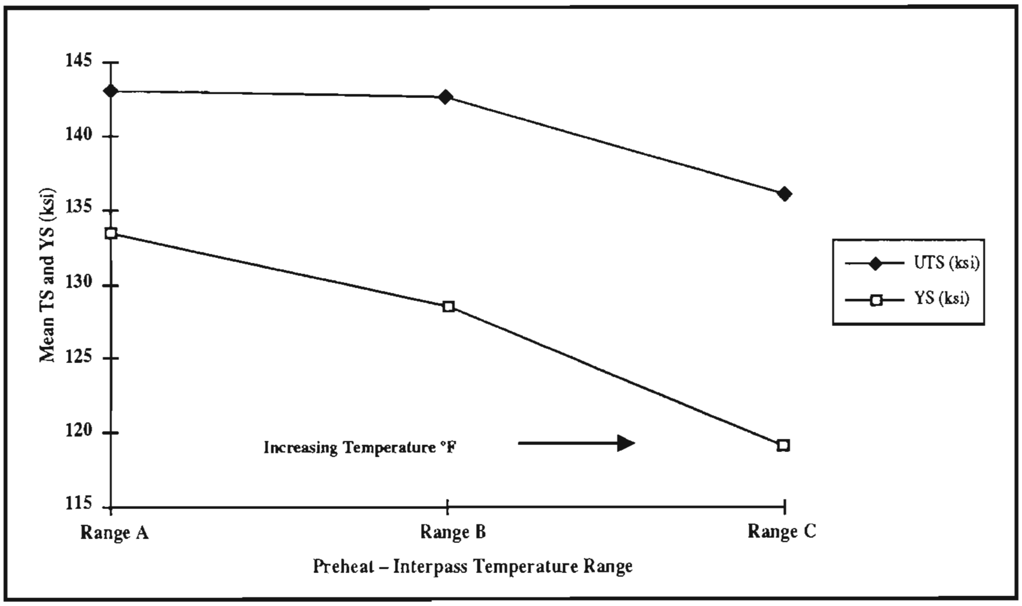

Chart 2

These results were expected, as lower preheat-interpass temperatures will allow a more complete transformation to a higher-strength structure. Thus, it becomes important to use the lower preheat-interpass temperature when a higher weld strength is desired. This lower preheat temperature will not cause weldability problems except under high-restraint conditions.

Charpy Impact Testing

All-Weld Impact Tests

A Fracture Appearance Transition Temperature (FATT) curve was run for al-weld metal specimens. The curve yielded a 50% ductile/brittle fracture appearance ($FATT_{50}$) at -25°F. The room temperature impact strength was 114 ft. lbs. This

All-Weld Impact Tests

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was compared to typical combustion turbine disc properties of -45°F and 72 ft.lbs., respectively. As expected, the weld is superior in impact strength. The $FATT_{50}$ is above nominal design but is not a concern because it is well below the operating service temperature.

Heat-Affected Zone Impact Tests

Another FATT curve was run with the notch centered in the HAZ. The curve yielded a $FATT_{50}$ at -70°F and a room temperature impact strength of 94 ft.lbs. These results show the heat-affected zone has better toughness than the unaffected disc. This is due to the fine-grain, martensitic structure of the heat-affected zone compared to the coarser-grained, bainitic structure of the unaffected disc. Both the disc and heat-affected zone data meet the nominal material property requirements.

High-cycle Fatigue

Smooth bar and notched ($K_t = 2.45$) high-cycle fatigue tests were conducted on all-weld metal and notched specimens on the heat-affected zone. The testing was performed in the axial direction in air at room temperature. The test results were compared to the disc material at 140 ksi Y.S. and are shown in the following table. The data has been normalized with respect to the disc material.

		Endurance Limit (ksi)		
Type Specimen	**Mean Stress (ksi)**	**Weld Metal**	**Heat Affected Zone**	**Base Metal @ 140 ksi Y.S.**
Smooth	0	.89		1.00
Smooth	40	.93		1.00
Notched	0	.94	1.12	1.00
Notched	40	.79	1.14	1.00

Table 4

This data summary shows the weld has an endurance limit slightly below the disc material, which is expected because of the lower tensile strength of the weld metal. The heat-affected zone has a slightly greater endurance limit than the 140 ksi disc material.

Hardness

The final area of testing, hardness readings (Rockwell C), were taken across the weld, fusion line and HAZ and are summarized below:

Location	**Hardness High**	**Hardness Low**
Weld	35	31
HAZ	42	37
Base Metal	33	30

Table 5

Although the HAZ readings were three to five points higher than the baseline data base, the higher hardness did not adversely affect the impact properties.

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Production Case Studies

Although the results of the weld testing did not achieve the goal of 140 ksi yield strength, the strength and other property values obtained are acceptable for many repairs on combustion turbine discs. The program was then released to begin repair on combustion turbine parts on a part-by-part approval basis. The following two case studies are representative of the type of combustion turbine repair welds made to date.

Production Case #1: End of Rotor-Disc/Journal

The first example of a weld repair on combustion turbine discs is a repair of mechanical damage on the end of a disc forging in the journal area. The disc is shown in Figure 1:

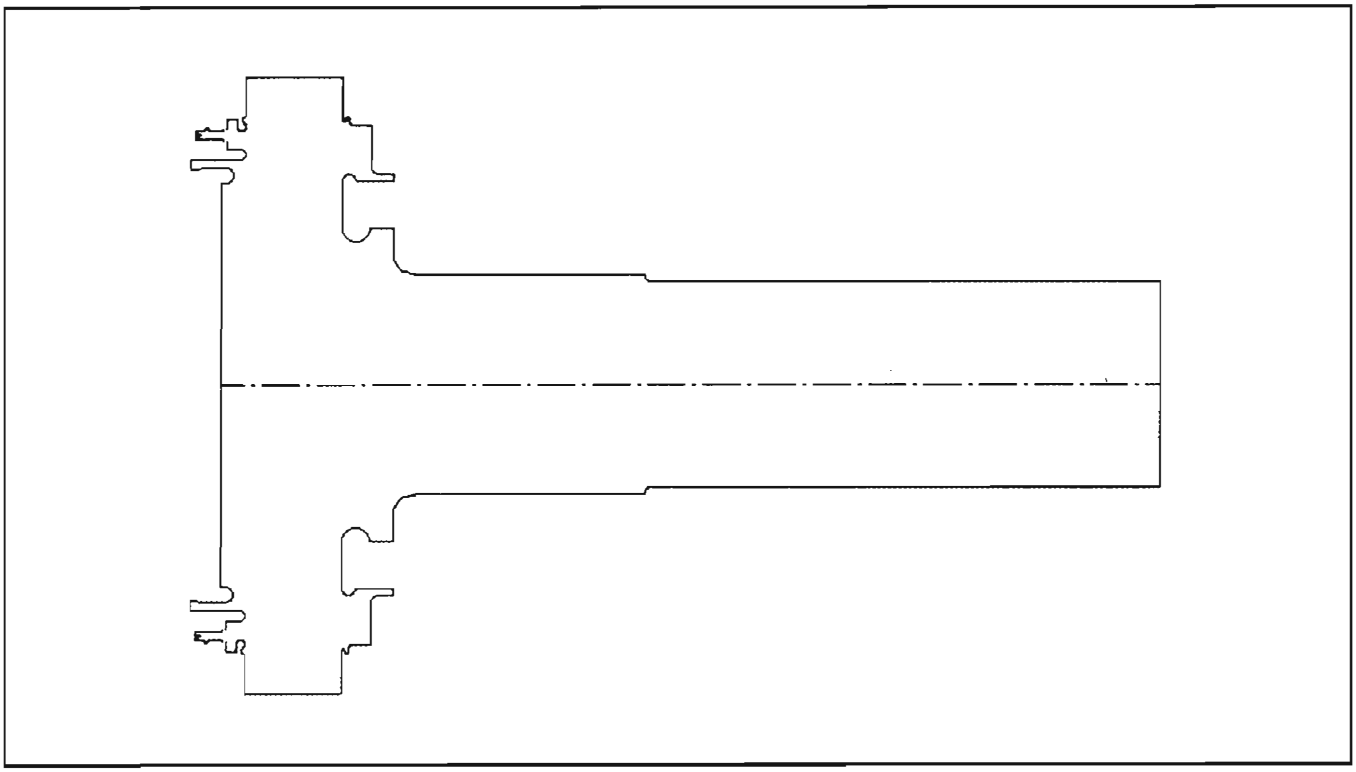

Figure 1. Combustion Turbine Disc 4

Rather than machine the journal area undersize, which would require special bearings, the decision was made to weld build-up the entire journal area as shown in Figure 2. This figure is an expanded view of the middle of the disc shaft section.

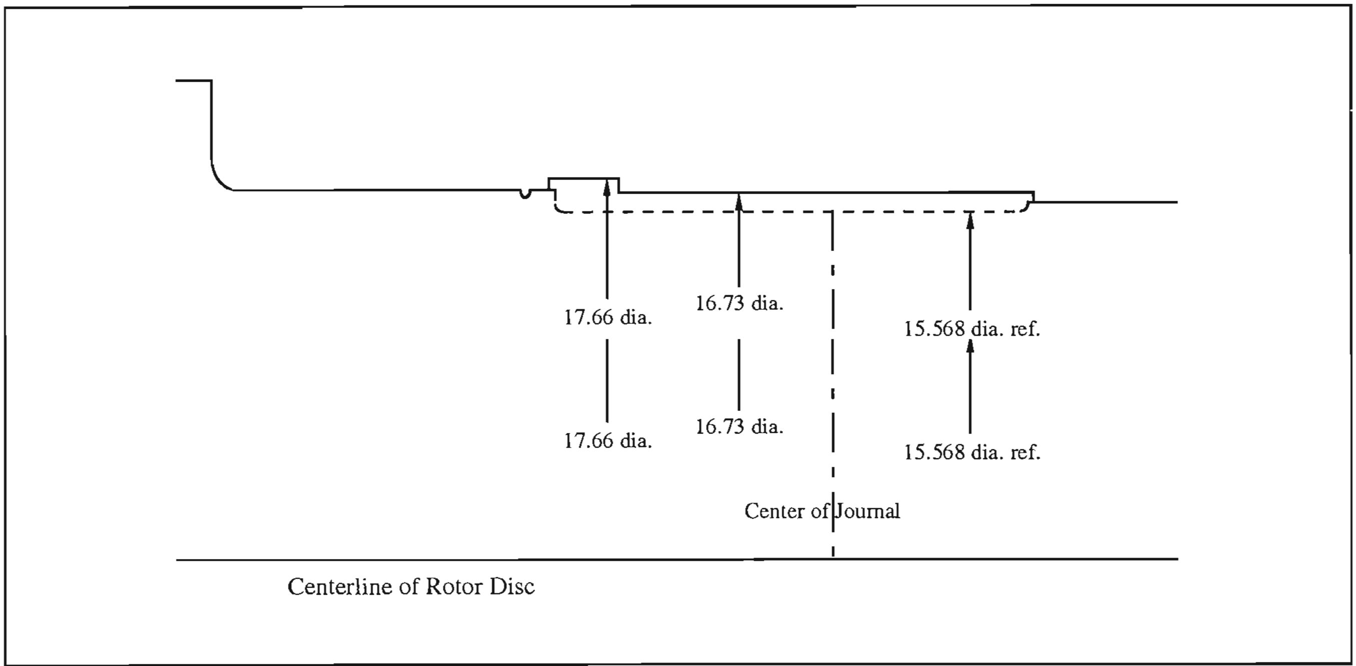

Figure 2. Weld-Repair Area on Journal

Although the mechanical damage did not involve the entire journal area, it was not desirous to leave the HAZ anywhere in the journal area. Thus, the weld extended past both ends of the journal area. Once the weld was made, it was inspected by UT and MT prior to receiving a stress-relief heat treatment. Following heat treatment, the weld was reinspected by UT and MT prior to the disc being machined back to its original contour.

During final machining of the disc, the runout was checked for as little as .0001" and no distortion to the shaft was observed. The hardness of the weld was also checked and met the requirements.

Production Case #2: Compressor End Thrust Collar

Another repair was made to the thrust collar on the compressor end of a combustion turbine rotor. The thrust collar needed to be expanded in width to facilitate a design change. A sketch of the compressor end of the combustion turbine rotor is shown in Figure 3.

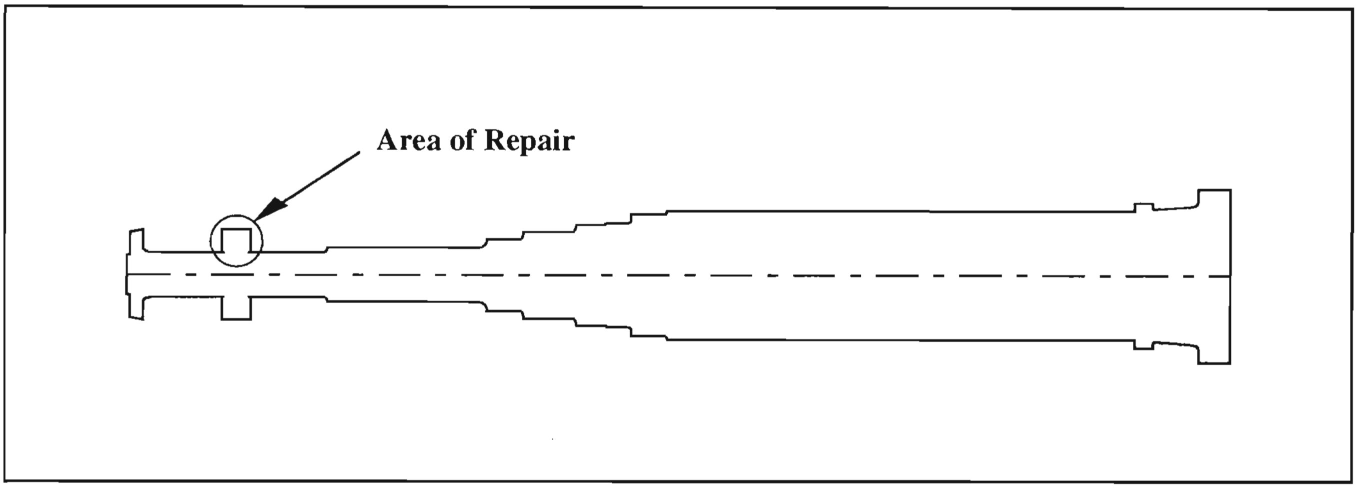

Figure 3. Combustion Turbine Compressor Rotor

The original thrust collar was machined to a width of 3.065". The design change called for the width to be expanded to 3.580". Figure 4 shows the weld build-up and the final machined configuration of the thrust collar.

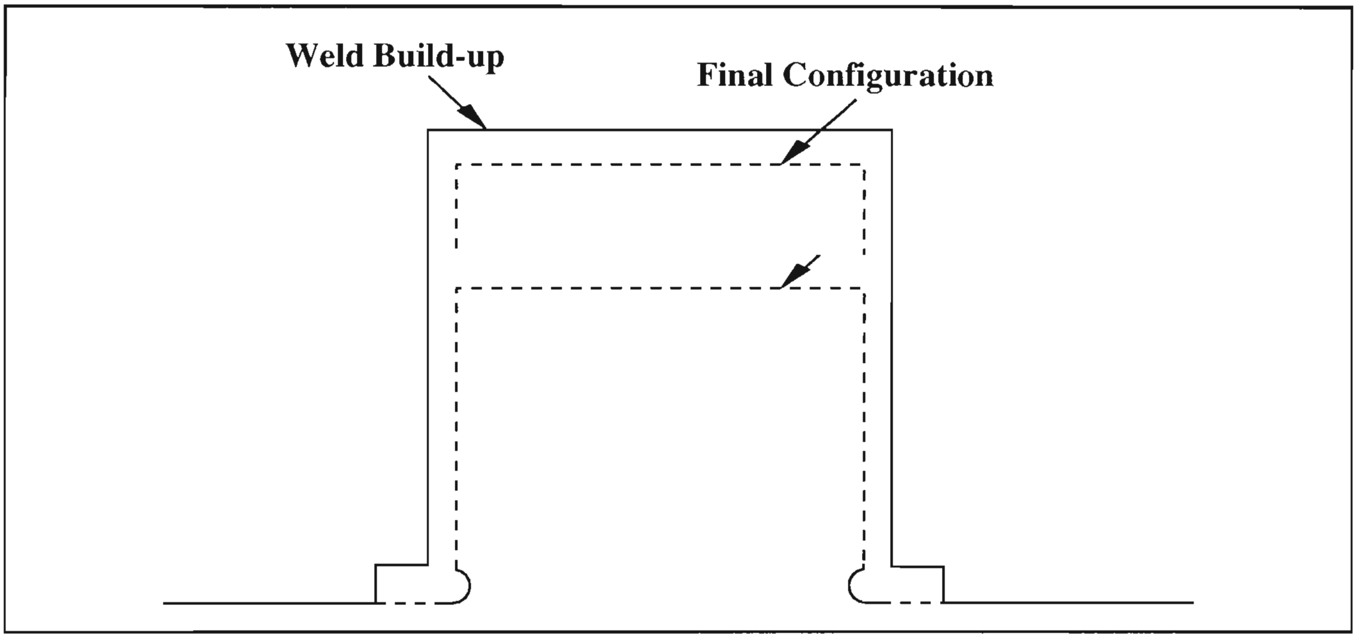

Figure 4. Weld Repair of Thrust Collar

Following the weld repair, the rotor was inspected, stress relieved and retested just like the first production weld-repaired disc. The weld met the requirements and the rotor was restored to drawing.

Future Work

As seen previously in this paper, the initial weld metal qualification program did not meet the original objective of 140 ksi yield strength minimum. Although this allows welding on many areas of the combustion turbine rotor that do not require 140 ksi yield strength and the service temperature is under 700°F, it is still desirable to qualify a program that produces welds in the 140–145 ksi yield strength range. Westinghouse has outlined two possible programs to achieve this goal.

Development Of A High Strength (145 ksi Y.S.) Filler Wire

This program would seek to achieve a minimum 140 ksi yield strength weld by modifying the nominal "W140" chemical composition. These modifications are anticipated to result in yield strengths of 145 ksi without seriously affecting toughness. A detailed model was developed for predicting yield strength based on the chemical composition of lower strength wires. Using this model, general predictions can be made for the higher strength levels. These predictions have been compared with heats of wire that have already achieved high strength levels. The current program outline calls for changing several of the main alloying elements. These changes are predicted to increase the yield strength from the current 135 ksi to 145 ksi nominal. These changes represent a move from the "W140" toward a high strength version of our existing LP wire chemistry.

Welding Procedure Modifications

This program would seek to produce the nominal 145 ksi yield strength welds by modifications to the welding parameters. Test plates have already been produced with modifications to the overall heat input during the welding process. While this program may yield a higher-strength weld by itself, it could also be utilized in conjunction with a filler metal chemistry change.

Conclusions

The following points provide a brief summary of the rotor welding capability at Westinghouse and our current efforts at welding on combustion turbine rotors:

- Westinghouse has an established service record of successful weld repairs on LP rotors since 1983 and on HP rotors since 1988.
- Hundreds of welds have been made on both HP and LP alloys without a single weld-related service failure.
- The success of these programs gave incentive to develop a high strength weld for combustion turbine alloys.
- The initial combustion turbine development program resulted in a weld with a nominal 135 ksi yield strength, which

rotors since 1988.
- Hundreds of welds have been made on both HP and LP alloys without a single weld-related service failure.
- The success of these programs gave incentive to develop a high strength weld for combustion turbine alloys.
- The initial combustion turbine development program resulted in a weld with a nominal 135 ksi yield strength, which

allows weld repair in many areas of the rotor that do not require full strength and have service temperatures below 700°F.
- Three combustion turbine parts have been successfully welded with one other presently in process.

Acknowledgments

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